LCA-based evaluation of ecological impacts and external costs of current and new electricity and heating systems

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ABSTRACT

A systematic study of current European electricity and heat systems performed in the frame of the Swiss LCA project ecoinvent was extended to a few new technologies and used as a basis for comparison and ranking using External Costs Assessment and one selected Life Cycle Impact Assessment (LCIA) method. The energy systems include full process chains from extraction of resources through waste disposal. The external costs from airborne emissions were estimated using the most recent findings of the ExternE series on the average damage factors for Europe.

Current fossil electricity systems exhibit the highest LCIA scores as well as the highest external costs, unless greenhouse gas emissions (GHG) are valued very low (sensitivity) and advanced technologies are applied. Alpine hydropower always exhibits the lowest score. Environmental performance of current renewables is generally better than fossil but LCIA ranking for wind and PV may worsen when increased importance is attributed to abiotic resource depletion. Wood cogeneration has a relatively poor score compared to other renewables. Nuclear shows generally good environmental performance, unless the high radioactive wastes are given subjectively high negative value. For heating systems, oil has higher external costs than natural gas, with conventional wood in between. External costs of heat pumps strongly depend on the origin of the electricity supplied.

Sensitivity analyses were performed for external costs to reflect uncertainties of impacts and variations in monetary valuation. Fossils remain worst performers. External costs of nuclear remain low. Using allocation by exergy, electricity by diesel and natural gas cogeneration ranks worse than oil and natural gas combined cycle, respectively, and never better than renewables or nuclear.

INTRODUCTION

The results of two different aggregation methodologies for the valuation of environmental impacts of energy (electricity and heating) systems are discussed herewith, namely Life Cycle Impact Assessment (LCIA) and External Cost Assessment. Although the technologies analyzed with these two methodologies are based on the same Life Cycle Assessment (LCA) study [1], LCIA results will be shown for selected current electricity technologies only, which is sufficient for illustrative purposes and deriving conclusions on ranking of systems and inter-comparison with external cost results from [2].

INVENTORY DATABASE

The ecoinvent database is a commercial, centralized, web-based LCA database (www.ecoinvent.ch), developed and implemented by the Institutes of the Domain of the Swiss Federal Technical University, which created the Swiss Centre for Life Cycle Inventories, supported by Swiss Federal Offices [3]. The presented results are based on version v1.1 online since August 2004, with a few corrections for LCIA (e.g., particle emissions during hydro dam construction).

The sectors included in the Life Cycle Inventory (LCI) background database are: energy systems; materials & metals; waste treatment & disposal; transport systems; chemicals; and, agricultural products. About 2750 individual processes have been modeled based on full process analysis, and about 1000 elementary environmental flows inventoried, including emissions to air, water and soil, solid wastes, land use, as well as biotic and abiotic resources. The cumulative environmental burdens calculated for the processes reflect all interactions within the economy system modeled in ecoinvent. Besides LCI, ecoinvent includes also LCIA results using current methods developed by different organizations. The assessed energy systems, reflecting European conditions around year 2000, make about half of the processes available in ecoinvent. They include electricity and heating systems [1]. Electricity transmission & distribution as well as country/region-specific[1] production and supply mixes were also modeled.

An energy systems includes all industrial activities directly and indirectly linked with the conversion of an energy carrier (fossil, nuclear) or renewable energy source (solar, wind, hydro), from extraction of resources up to the point of its conversion to useful energy (electric, heat, or mechanical), and including waste management.

The goal of the analysis of current and selected new energy systems pursued in the study [2] was integrating LCA with external cost assessment for airborne pollution. This was achieved by combining the detailed and internally consistent LCI in ecoinvent with damage factors based on the impact-pathway approach. These calculated inventories do not contain explicit information on the location of the contributing emission sources. Therefore, the external costs were calculated based on average damage factors for emissions in Europe.

ENERGY TECHNOLOGIES

The main characteristics of current and new electricity and heating systems considered in [2] are given in Tables I and II, respectively.

Current technologies

Coal – Information on several individual coal power plants in Europe was used for determining country-specific averages. Hard coal mining has been addressed for eight production regions in the world. In general, there are substantial differences for country-specific cumulative results.
Oil - The average UCTE power plant includes base load as well as medium and peak load conventional plants. The oil energy chain is composed of field exploration, crude oil production, long distance transportation, oil refining, regional distribution, and boilers/power plants.
Natural Gas - The upstream energy chain includes gas field exploration, natural gas production, natural gas purification, long distance transportation, and regional distribution in high and low pressure networks. The gas supply shares in Europe in year 2000 are: 5% Germany; 24% The Netherlands; 34% Russian Federation; 17% Norway; 16% Algeria/North Africa; and, 4% UK.

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[1] Herewith mentioned is the UCTE, Union for the Co-ordination of Transmission of Electricity (UCTE). The UCTE countries in year 2000 were: Austria, Belgium, Bosnia Herzegovina, Croatia, France, Germany, Greece, Luxembourg, Macedonia, the Netherlands, Portugal, Serbia and Montenegro, Slovenia, Spain, and Switzerland.

Table I. Characteristics of the electricity systems analyzed in [2] after ecoinvent [1,3].

Energy Source / Technology	Identifier in Figure 1 and 2	Technology description	Net efficiency (%)	Allocation exergy to el. (%)	Notes
Coal	Lignite	Average present plant for UCTE & energy chain	39	-	Installation of more efficient units and scrubbers will somewhat reduce external costs
	Hard Coal	Average present plant for UCTE & energy chain	36	-	Installation of more efficient units and scrubbers will somewhat reduce external costs
	Hard Coal PFBC	Pressurized Fluidized Bed Combustion (PFBC) power plant, technology around 2010 & present coal chain for Germany	47	-	• Efficiency may improve to 50% • The coal chain may differ in future (origin of the coal)
Oil	Oil	Average present plant for UCTE & energy chain	38	-	• The average includes base load and peak plants • Heavy oil used
	Oil CC	Combined Cycle (CC) best present technology & present oil chain for Europe	57.5	-	• Can be assumed for new units • Net efficiency may increase up to 60% • External costs roughly inversely proportional to efficiency increase
Natural gas	Gas	Average plant for UCTE & energy chain	38	-	
	Gas CC	Combined Cycle (CC) best present technology & present gas chain for UCTE	57.5	-	• Can be assumed for new units • Net efficiency may increase up to 60% • External costs roughly inversely proportional to efficiency increase
Nuclear	LWR	Average Light Water Reactor (LWR) for UCTE & close fuel cycle	33	-	• Damage factors for radioactive emissions approximated by DALY • Not all isotopic species have been given a damage factor
	PWR (centrifuge enrichment)	Average Pressurized Water Reactor (PWR) for Switzerland & close fuel cycle with centrifuge enrichment only	32	-	• Can be assumed approximately for Advanced LWR, if the chain remains unaltered • In the current assessment, external costs associated with power plant are only a few percent of total
Hydropower	Hydropower (alpine)	Average reservoir plant for Switzerland & relevant energy chain	78	-	• Small improvements in average efficiency expected (84%) • May not be representative for specific units/sites for different material intensity for the dam and different flux of greenhouse gases from reservoir surface
Photovoltaic	PV panel (S-Europe)	Average present technology for monocrystalline-Si 3 kWp grid-connected units manufactured in Europe, panel mounted on slanted roof, average irradiation in South Europe (1200 kWh/ kWp /a)	12 (16.5 cell)	-	• External costs inversely proportional to irradiation (for Central Europe it can be assumed average irradiation of 800 kWh/ kWp /a) • Boundary of system include inverter • The inventory may not be valid for systems produced outside Europe, for production technologies and electricity supply mixes for manufacturing might be different
	PV integrated (S-Europe)	Same as above but with panel integrated in roof		-	
	PV integrated fut. (S-Europe)	Near future technology for monocrystalline-Si 3 kWp grid-connected units manufactured in Europe, panel integrated in slanted roof, average irradiation in South Europe (1200 kWh/ kWp /a)	13 (17.5 cell)	-	• Near-future scenario for purified silicon production and improved cell technology • Can be assumed for units around 2010
Wind	Wind onshore 800 kW	Present technology, average capacity factor in Germany (20%)	25	-	• External costs inversely proportional to capacity factor • Lower external costs with higher nominal power rate
	Wind offshore 2 MW	Current technology, shallow sea, reference capacity factor (30%) applicable near cost of North Sea (Middelgrunden, Denmark)	25	-	• As above for onshore • Environmental inventories and associated external costs may differ with depth of sea
Cogeneration Diesel	cogen diesel SCR 200 kWe	Modern diesel unit, installed in Europe, using Selective Catalytic Reduction (SCR) and an oxidation catalyst	39 (el.) 43 (th.)	85	New units & associated average European oil chain
Cogeneration Natural gas	cogen gas lambda=1, 160 kWe	Modern Lambda=1 motor gas cogeneration plant in Europe, using three-way catalytic converter	32 (el.) 55 (th.)	77	• New units installed & associated average Central European natural gas chain. • Different gas origins may change the contribution from the upstream chain to external costs
	cogen gas lean burn 1 MWe	Modern gas cogeneration plant in Europe, without catalysts	38 (el.) 44 (th.)	84	

* Boundary for the analysis is the busbar of the power plant.

Table II. Characteristics of the heating systems analyzed in [2] after ecoinvent [1,3].

Energy Source / Technology	Identifier in Figure 3	Technology description*	Net efficiency** (%)	Allocation exergy to heat (%)	Notes
Natural gas	cond-mod <100 kW	Modern boiler condensing, modulating	102	-	• New units & average Central European natural gas chain • Different gas origins may change the contribution from the upstream chain to external costs
	cond-mod >100 kW		102	-	
	mod <100 kW	Modern boiler modulating	96	-	
	mod >100 kW		96	-	
	industrial >100 kW	Modern industrial boiler	95	-	
Oil	heavy oil, industrial 1 MW	Currently installed industrial boiler	95	-	• New units & average European oil chain
	light oil, cond- non-mod 10 kW	Modern boiler condensing, non modulating	100	-	
	light oil, cond- non-mod 100 kW		100	-	
	light oil, non-mod 10 kW	Modern boiler non-modulating	94	-	
	light oil, non-mod 100 kW		94	-	
	light oil, industrial 1 MW	Currently installed industrial boiler	94	-	
Wood	logs heater 6 kW	Modern fireplace	75	-	• Available on market in 2000 & average Swiss soft & hard wood mix. • Can be used for central European conditions in the 2000s (no major changes in efficiency expected)
	logs 30 kW	Modern boiler burning logs, including water storage	68	-	
	logs 100 kW		70	-	
	chips 50 kW	Modern boiler burning chips produced at forest	80	-	
	chips 300 kW		82	-	
Cogeneration Diesel	SCR 200 kWe	Modern diesel unit, installed in Europe, using Selective Catalytic Reduction (SCR) and an oxidation catalyst	39 (el.) 43 (th.)	15	New units & associated average European oil chain
Cogeneration Natural gas	Mini 2 kWe	Modern Lambda=1 motor gas cogeneration plant in Europe, monovalent operation	25 (el.) 65 (th.)	27	• New units & average Central European natural gas chain • Different gas origins may change the contribution from the upstream chain to external costs
	lean burn 50 kWe	Modern gas cogeneration plant in Europe, without catalysts	30 (el.) 54 (th.)	23	
	Lambda=1, 160 kWe	Modern Lambda=1 motor gas cogeneration plant in Europe, using three-way catalytic converter	32 (el.) 55 (th.)	23	
	lean burn 500 kWe	Modern gas cogenneration plant in Europe, without catalysts	36 (el.) 46 (th.)	18	
	lean burn 1 MWe		38 (el.) 44 (th.)	16	
Heat Pumps	air-water 10 kW UCTE-el.	Modern present technology, SPF = 2.8, UCTE electricity mix in year 2000	280***	-	• UCTE electricity mix (2000) = Lignite 11.7%, Hard coal 14.5%, Oil 6.4%, Natural Gas 12.6%, Industrial gases 1.6%, Nuclear 35.6%, Hydro 14.7%, Wind & PV 0.8%, rest (incl. pumped storage & small cogeneration) 1.7% • Refrigerant R134a
	brine-water 10 kW UCTE-el.	Modern present technology, 150 m deep borehole, SPF=3.9, UCTE mix in year 2000	390***	-	
	air-water 10 kW future CC-el.	Future technology, SPF = 4.2 (seasonal performance factor), electricity from gas CC	420***	-	Technology level expected in 2020-2030
	brine-water 10 kW future CC-el	Future technology, SPF = 5.0, electricity from gas CC	500***	-	
	air-water 10 kW future nuclear-el.	Future technology, SPF = 4.2 (seasonal performance factor), nuclear electricity	420***	-	
	brine-water 10 kW future nuclear-el.	Future technology, SPF = 5.0, nuclear electricity	500***	-	

* Boundary for the analysis is the outlet of the boiler/cogeneration unit; the distribution in house is excluded. The given unit capacity is representative of a class more than of a specific boiler/cogeneration unit.
** Calculated on the basis of the Low Heating Value (LHV) of the fuel. *** Based on SPF = Seasonal Performance Factor (yearly averaged Coefficient Of Performance, COP).

Nuclear - Two systems are considered: the average currently installed UCTE nuclear power plant of the Light Water Reactor (LWR) type, with partially closed nuclear cycle; and, a currently installed typical Pressurized Water Reactor (PWR) of the 1000 MW class with a closed cycle including centrifuge enrichment only, which can be assumed as reflecting near future conditions of enrichment supply. The stages modeled were: conventional mining, conversion, enrichment (diffusion and centrifuge), fuel fabrication, PWR, BWR (Boiling Water Reactor), reprocessing, spent fuel conditioning, interim storage, low level radioactive waste depository, and final geological repositories of highly and intermediate level radioactive wastes (Swiss case).
Hydro Power - The average Swiss reservoirs with concrete dams were modeled, and extrapolated to Europe. Average run-of-river and pumped storage plants are in ecoinvent, but were not addressed in [2]. Small amounts of GHG emitted from Alpine reservoirs during operation may not apply to other site-specific conditions – see discussion in [4].
Photovoltaic - The production stages, reflecting conditions around year 2000, include: silica sand production, metallurgical-grade silicon production, silicon purification, Czochralski monocrystalline silicon production, polycrystalline silicon production, wafer production, cell manufacturing, panel or laminate production; these stages are assumed to take place in different European countries. Only 3 kW_{peak} photovoltaic plants were considered. The boundary for the analysis includes the Balance Of System (BOS) up to the grid. Here shown are only results for the monocrystalline silicon, slanted roof panel applications. Average South European irradiation conditions are assumed. Results can easily be extrapolated to other conditions by multiplying them with the appropriate ratio of yields. Lifetime assumed is 30 years.
Wind Power - Two systems are addressed for external costs calculation: an onshore 800 kW wind turbine with 20% capacity factor (CF), average for Germany; and, a 2 MW offshore wind power plant, based on the wind park Middelgrunden, Denmark, with CF 30%. Results can be scaled up/down with the appropriate CF ratio. However, the results for the offshore plant may not be directly scalable for different conditions of water depth and distance from the coast.
Wood Energy - Several classes of wood logs and chips furnaces have been modeled, representing average technologies available on the central European market around year 2000. Mixed wood is assumed to be directly taken from forest (72% softwood and 28% hardwood, representing the Swiss commercial wood mix around year 2000).
Heat Pumps - Two wide-spread types of 10 kW HPs for one-family houses are modeled: an air-water HP and a brine-water HP. The boundary is set at the HP outlet before heat distribution. An average location in Europe is considered, for which the average UCTE electricity mix is used.
Cogeneration - Different types of small natural gas and diesel units are included.

New technologies

Fossil - Three new power technologies have been assessed: the Pressurized Fluidized Bed Combustion (PFBC) coal power plant, technology around 2010, and the oil/natural gas Combined Cycle (CC) technology available today. With reasonable approximation, the external costs (with current damage factors, though) for these technologies in a longer time horizon can be obtained just by scaling the results with the ratio of net efficiencies, because not much can be expected for further reduction of direct emissions nor dramatic changes in upstream chains. Future fossil heating systems are not expected to have their net efficiency improving much further. Hence, the shown external costs should hold also for near future fossil boilers.

Nuclear - Advanced LWR (ALWR) will have better net efficiency (35%) than current LWR, longer lifetime (60 years vs. 40 years), reduced material intensity for construction of the power plant, and higher fuel burn-ups; emitted radionuclides during operation should remain approximately comparable with the current plants, because limited by site characteristics. Emissions from reprocessing should remain about similar, unless lower standards would be issued by the Regulatory bodies. Emissions from mill tailings may reduce if reclamation standards will become stricter worldwide. Therefore, external costs from releases to environment may somewhat decrease. Hence, from this perspective current results could be used for representing upper values for systems with ALWR.
Revewables - Substantial improvements of net efficiency are not expected for wood logs and chips furnaces. Decreases in external costs would result from applying NO_x and PM control technologies, but these are cost-effectively applied only in larger (centralized) units. Substantial reductions of the inventories are expected for PV. Inventories for wind power change depending on the turbine power rate, CF, and on water depth and distance from the coast for off-shore.
Heat Pumps - To estimate the effect of advancements in technology and differences from the electricity supply, the external costs of the two HP systems were estimated for technology in year 2020-2030 [5] supplied by either gas CC or nuclear power (PWR with centrifuge only).

EXTERNAL COST ASSESSMENT

Base damage factors

Major outputs of LCA are cumulative emissions from complete energy chains resulting from all modeled interaction within the economy system described in the ecoinvent database. In order to estimate the related external costs, average damage factors per tonne pollutant have been used, as shown in Table III.

Table III. Base case and sensitivity damage factors per tonne of pollutant emitted. All cases but the last refer to emissions in the EU15 countries.

	Damage factors [€$_{2000}$/tonne]				
Species	Base Case	Sensitivity Local	Sensitivity CO_2-equivalent Low	Sensitivity $PM_{10}/PM_{2.5}$	Sensitivity EU25
CO_2-equiv.	19	19	1	19	19
SO_2	2939	3524	2939	2939	3312
NO_x	2908	3021	2908	2908	3054
PM_{10}	11723	27042	11723	11723	11437
$PM_{2.5}$	19539	45070	19539	11723	19062
$PM_{2.5-10}$	0	0	0	11723	0
Arsenic	80000	80000	80000	80000	80000
Cadmium	39000	39000	39000	39000	39000
Chromium	31500	31500	31500	31500	31500
Chromium-VI	240000	240000	240000	240000	240000
Chromium-other	0	0	0	0	0
Lead	1600000	1600000	1600000	1600000	1600000
Nickel	3800	3800	3800	3800	3800
Formaldehyde	120	120	120	120	120
NMVOC	1124	1124	1124	1124	1128
Nitrates, primary	5862	13521	5862	5862	5719
Sulfates, primary	11723	27042	11723	11723	11437
Radionuclides emission	50000 * [€$_{2000}$/DALY]	50000 * [€$_{2000}$/DALY]	50000 * [€$_{2000}$/DALY]	50000 * [€$_{2000}$/DALY]	50000 * [€$_{2000}$/DALY]

* Disability-Adjusted Life Years (DALY), assuming equal to the unit value of chronic YOLL (Years Of Life Lost).

The factors refer to the most important airborne pollutants, and take into account the latest advancements of external costs methodology in NewExt, DIEM and ExternE-Pol projects of the European Commission. The factors represent an average location of the emission sources in EU15. With this simplified approach, the same factors have been applied to all parts of the chain. The damage factors for SO_2, NO_x, and PM_{10} are based on regional calculations of the EcoSense multi-source version for a 50 km × 50 km grid [6]. The factors for CO_2-equivalents, $PM_{2.5}$, heavy metals, for formaldehyde and for NMVOC (lumped without any weighting factor applied to the masses) are adopted from NewExt [7] and ExternE-Pol [8]. In order to include a rough estimate of the damages due to radioactive emissions, the Disability-Adjusted Life Years (DALY) concept implemented in the LCIA method Eco-indicator ’99 [9] has been used. The monetary value of a DALY was set equal to the monetary value of a life year (the latter is derived in the valuation part of the NewExt study).

External cost results

The external costs per kWh are calculated by multiplying the cumulative emissions of each system with the base case damage factors (Table III). Cumulative emissions from cogeneration systems have been allocated using the exergy concept.

Fig. 1 shows an overview of the results for current and new electricity systems. Fig. 2 gives the calculated contributions of the species to total external costs. Numerical results on cumulative emissions of the species or groups used in the pictures are provided in [2].

Current fossil systems for the generation of electricity exhibit the highest external costs, in the range of 1.6 to 5.8 c€/kWh. Introduction of advanced technology substantially reduces external costs, but they still remain in the range of 1 to 2 c€/kWh. Oil technologies cause higher external costs than comparable gas technologies.

Nuclear external costs are below 0.19 c€/kWh, of which at least 95% from upstream and downstream contributions, i.e. the power plant contributes 5% or less to external costs from the cycle. Of these calculated costs, 70% are due to radionuclides. However, by discounting, this contribution would strongly decrease, because most of the calculated relevant damages are either related to very long term emissions (e.g., ^{222}Rn from uranium mill tailings) or to very long-lived isotopes giving very small dose rates.

Wind onshore with nearly 0.09 c€/kWh performs slightly better than wind offshore (0.12 c€/kWh). The reason lies in the higher material intensity and higher energy for the off-shore installation, which are not compensated by the assumed higher capacity factor. In this case, wind technology scores second best after hydropower and before nuclear.

Monocrystalline silicon PV panels installed in Southern Europe with an assumed yield of 1200 kWh a^{-1} kW_p^{-1} cause nearly 0.28 c€/kWh, which would mean 0.41 c€/kWh for an average yield of 800 kWh a^{-1} kW_p^{-1} in Central Europe. Assuming improvements in manufacturing technology of crystalline silicon, improved cell efficiency, and an expanded PV market, 0.21 c€/kWh is estimated for around year 2010 systems for South Europe [2]. External costs associated with imported panels may differ due to different manufacturing technology and electricity supply. Due to the relatively high material intensity of PV and wind, the contribution from heavy metals is substantial.

Alpine hydropower exhibits the lowest external costs, below 0.05 c€/kWh, but these may increase on sites with higher direct emission of GHG from the surface of reservoir [4] and where a higher material intensity or lower lifetime are calculated or assumed.

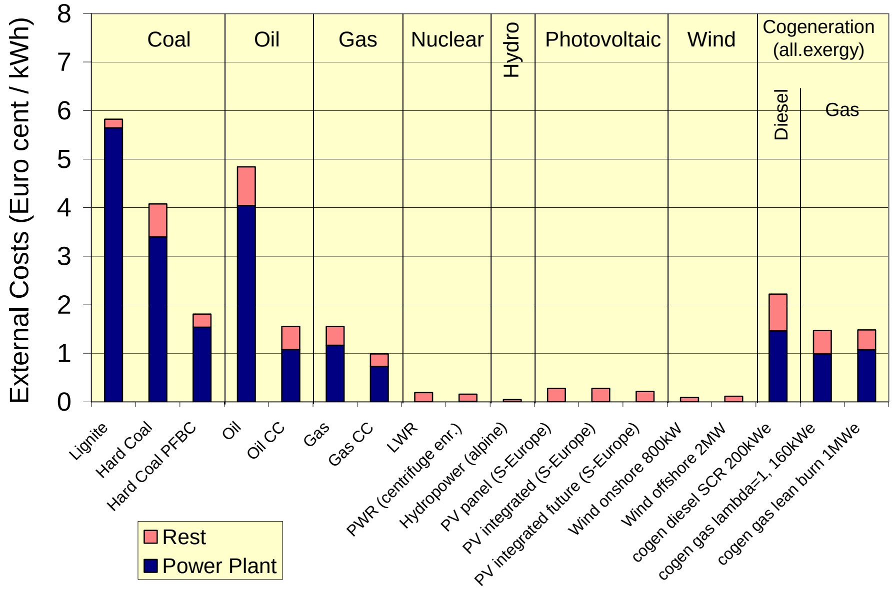

Figure 1. External costs of electricity for current European average and selected new systems, associated with emissions from the operation of power plants and the rest of energy chains.

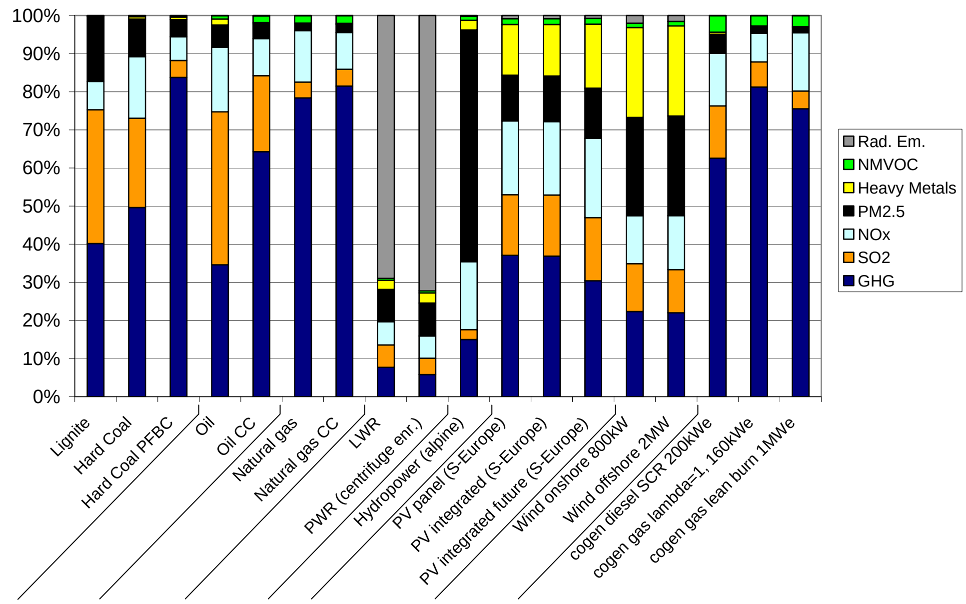

Figure 2. Contribution percent to external costs of electricity systems by species.

Figure 3 shows an overview of the results for modern and future heating systems. Details on contributions of the species to total calculated external costs are provided in [2]. For heating systems, in general gas boilers have lower external costs than boilers burning light oil. Burning heavy oil gives the highest damages. With the base case damage factors, modern wood boilers rank in between oil and gas modern heating technologies. PM and NO_x emissions contributing the most to total damages. The magnitude of external costs of HP is controlled basically by two factors: the Seasonal Performance Factor (SPF) and the electricity supply source. With a highly efficient fossil electricity source or nuclear power or a renewable source, HP exhibits the lowest external costs among the heating systems.

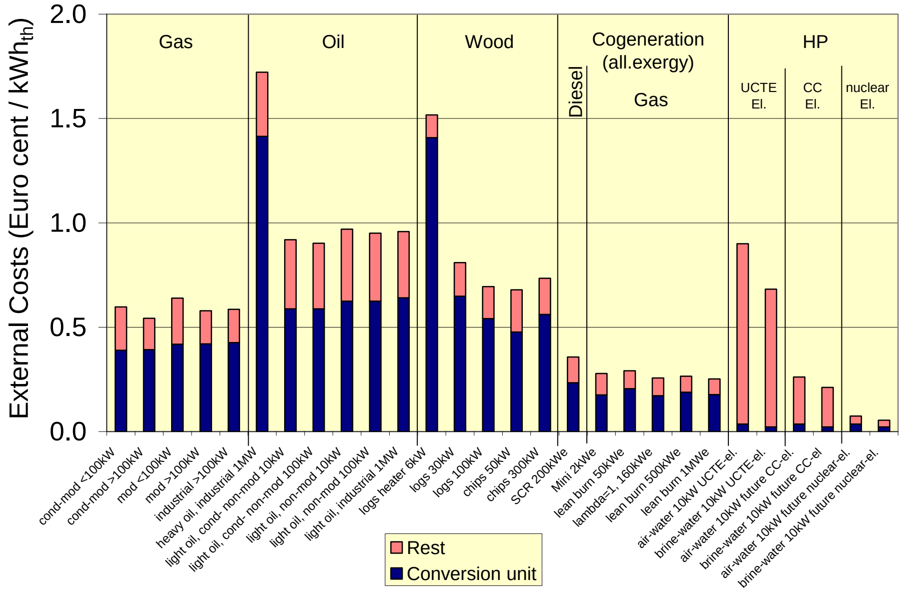

Figure 3. External costs of current European average heating systems and future heat pumps, associated with emissions from the operation of boiler/cogeneration unit and with the rest of energy chain.

Sensitivity analyses

Sensitivity analyses were performed in [2] reflecting on the one hand the uncertainties of impacts, e.g. due to unknown emission locations or due to uncertainties of impact functions, and on the other hand the sensitivity to monetary valuation. In order to give some indication about the sensitivity due to possible local effects as estimated in NewExt, the NewExt factors shown in Table III, column “Sensitivity Local”, have been applied. The factors differ from the base factors mainly for primary particulates. The impacts on human health per tonne emitted primary fine particulates can be very high if the emissions take place in highly populated areas.

The damage factor for GHG is extremely important for external cost estimates of fossil systems (Figure 2). The impacts resulting from global warming are notoriously difficult to model and to valuate in monetary terms. The base factor is comparable to the highest estimate in [10]. Therefore, the “Sensitivity CO_2-equivalent Low” case has been studied assuming a lower factor (1.0 Euro per tonne CO_2) from [10] based on CO_2 world average values with 3% PRTP (pure rate of time preference).

The details of the mechanism causing health damages of particulates is still not fully understood, and therefore it is uncertain whether the assumption made for the base case that all damage stems from $PM_{2.5}$ holds. Thus another sensitivity case (“Sensitivity PM_{10}/$PM_{2.5}$”) was studied including all PM_{10} treated with a common factor for PM_{10}.

The calculations have been repeated with damage factors for EU25 in order to estimate the sensitivity to a different extension of the emission source area. The modeling area of the impact assessment has not changed. The differences between the damage factors per tonne emitted pollutant for EU25 and the corresponding factors for EU15 are rather small.

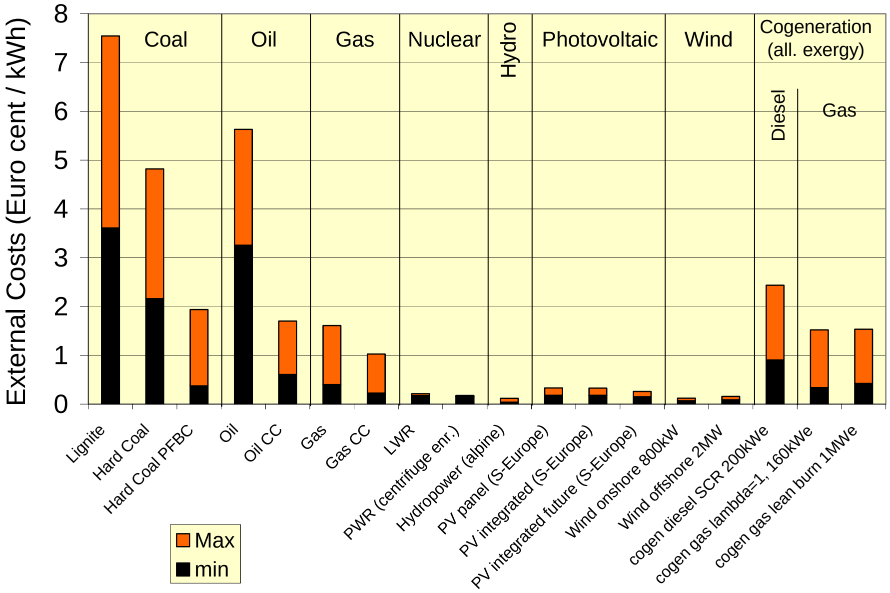

Figure 4. External costs of electricity for current European average and selected new systems: Range of values for sensitivity analyses covering uncertainty factors on impacts.

The results of the four sensitivity analyses for electricity systems are summarized in Figure 4. The results of individual sensitivity analysis and more sensitivity cases related to the variation of the monetary valuation of mortality impacts are discussed in [2].

For electricity systems, any change of damage factors basically does not change the relative ranking of fossil systems, with the exception of low factor for GHG emissions which may favor PFBC vs. oil CC. Fossil systems are always penalized by external costs, whatever the scheme for damage factors adopted. Hydropower (in alpine regions) always remains the best performer. With all sets, wind remains second best after hydropower.

LIFE CYCLE IMPACT ASSESSMENT

LCIA methods aim at providing a single measure of potential environmental effects from cumulative burdens. One LCIA method, Eco-indicator ’99 (EI’99) [9], has been exemplarily chosen because of its comprehensiveness and wide acceptance. EI’99 describes average environmental effects for emissions occurring in Europe. It is a damage-oriented method, which considers, by means of damage factors applied to the cumulative inventories, the effects of stressors in three damage categories: Human Health, Ecosystem Quality, and Resources. The different damage categories are normalized, and then weighted on the basis of the perspective of three typologies of stakeholders, identified using a cultural theory concept: Individualist, Egalitarian, and Hierarchist [9]. The Hierarchist has a balanced time perspective and requires consensus among scientists for consideration of a burden. The Egalitarian has a long term perspective and accepts potential effects even with minimum scientific evidence; ecosystem quality is on top of concerns. The Individualist has a short term perspective and only accepts effects which are proven; human health is in focus, whereas fossil resources are not given importance. Table IV shows the damage categories and the weighting factors suggested by [9] and implemented in ecoinvent.

Figures 5 to 7 show the results obtained applying EI’99 to selected current European average systems from ecoinvent. Assumed wind annual capacity factor is 20% and PV annual yield 1200 kWh a^{-1} kW_p^{-1}, consistently with the set used in external cost assessment. The wood cogeneration unit is a 6400 kW_{th}, 400 kW_e Swiss plant, burning natural wood chips; pollution control such as particle filter and Selective Non Catalytic Reduction is considered although not actually implemented. Currently operational, average European fossil systems have in general the worst environmental performance under all three perspectives, with the exception of gas for Individualist. However, under the Individualist perspective, mineral resources get a relatively high score (due to normalization values), thus renewables but hydro rank somewhat higher than gas. Hydro and nuclear perform best with all perspectives, but also wind performs similarly for the Hierarchist and Egalitarian. With Hierarchist and Egalitarian, wood cogeneration (allocation of impacts using exergy), is worst performer amongst renewables.

Table IV. Damage categories and weighting considered in Eco-indicator ’99 [9].

Life Cycle Inventory	Damage Midpoint Categories	Damage Categories	Individualist	Egalitarian	Hierarchist (Average)
Land occupation and transformation	Regional effect on vascular plants	Ecosystem Quality	25%	50%	40%
	Local effect on vascular plants				
NO_x, SO_x, NH_3	Acidification / eutrophication				
Pesticides, heavy metals	Ecotoxicity				
Greenhouse gases	Climate change	Human Health	55%	30%	40%
H/CFC, Halons	Ozone layer depletion				
Radionuclides	Ionizing radiation				
NO_x, SO_x, VOC, PM	Respiratory effects				
Heavy metals, PAH, dioxins,etc.	Carcinogenesis				
Minerals & fossil fuels	Surplus energy for future extraction	Resources	20%	20%	20%

COMPARYING EXTERNAL COSTS WITH LCIA

The rankings obtained with the LCIA method EI’99 and the External Cost Assessment for current European average electricity systems do not substantially differ from the qualitative point of view. The results of external cost sensitivity analyses show that ranking is sufficiently robust. For two of the perspectives in EI’99, Hierarchist and Egalitarian, fossils are further penalized by valuation of non-renewable resource, which is not included in the external costs.

It must be remarked that both rankings are limited to the environmental assessment, which includes human health effects. Consideration of private costs for comparison of total (private + external) costs would dramatically change the ranking, because direct cost of electricity from current renewables is in general more (wind, small hydro, wood cogeneration) or even much more (PV) expensive than fossil or nuclear. The differences of direct costs between fossil technology available today and renewables prevail on external costs, thus making renewables penalized in the ranking of total costs (e.g. [11]).

Furthermore, not all environmental interventions are covered by the shown external costs; some impacts are problematic to quantify in monetary terms.

Another limitation of the present comparison is that some important aspects of social relevance are not included in both methodologies. For example, for nuclear, proliferation, waste confinement times, and risks of very low-frequency, high consequences severe accidents, are factors of concern for some stakeholders but are only implicitly or not at all addressed by current

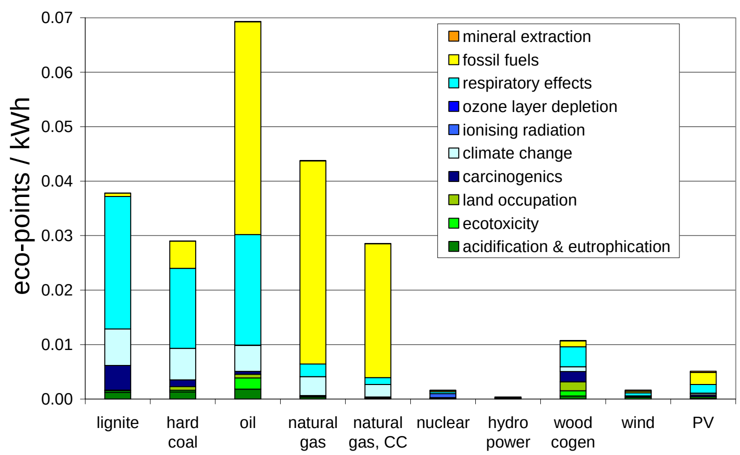

Figure 5. Eco-indicator 99 results for current European average electricity systems addressed in ecoinvent, Hierarchist perspective, average weighting.

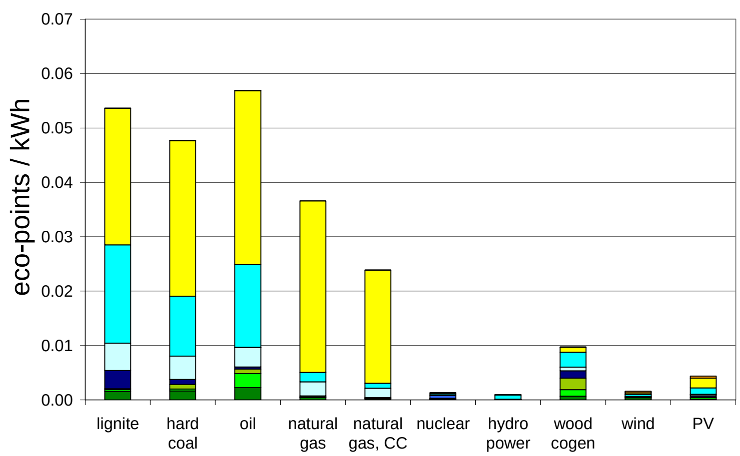

Figure 6. Eco-indicator 99 results for current European average electricity systems addressed in ecoinvent, Egalitarian perspective.

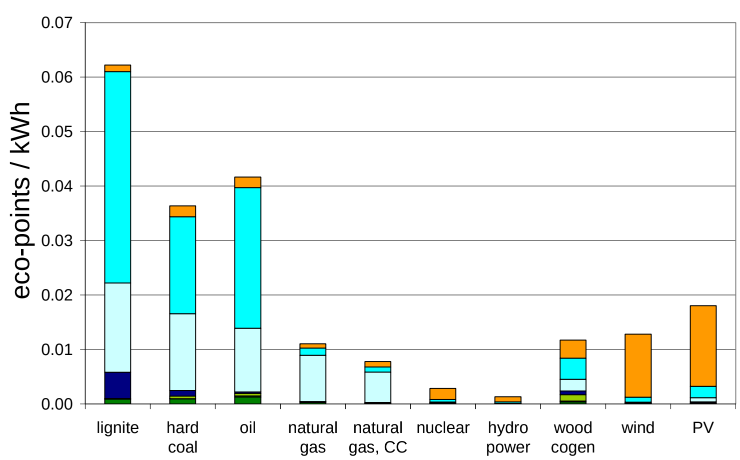

Figure 7. Eco-indicator 99 results for current European average electricity systems addressed in ecoinvent, Individualist perspective.

external cost assessments. Multi-criteria decision analysis (MCDA) tools can be used for an actually holistic approach for sustainability evaluation (e.g. [11]).

The results herewith shown do not include a full spectrum of future technologies. Although some figures shown for market available technology are relatively good approximation of near future electricity and heating systems, decisions making on future technologies shall be based on consistent and fair sets of data across all energy sources.

Other LCIA methods, developed with different approaches (e.g., target oriented), different scope, or for specific regions/countries, may give different rankings. Therefore the comparison here performed between the ranking of electricity systems obtained by one LCIA method and external costs estimation shall not be taken as ultimate rather as illustrative.

CONCLUSIONS

Use of environmental external costs and the selected LCIA method for providing a measure of environmental impacts of current and near future energy technologies leads to similar rankings of the systems. The external cost rankings are sufficiently robust to variations of impact factors and valuation schemes. However, it is recommended to extend the comparison including more complete and in case updated external cost estimations as well as additional LCIA methods. Large differences between countries in terms of average environmental performance of current technologies as well as differences of impacts due to site characteristics may need to be considered depending on the scope of comparisons.

Comparison of future systems for decision making for medium to long term energy choices should be based on a set of data where all technology options are treated consistently and fairly. However, preliminary conclusions can be taken on the basis of the comparison herewith illustrated. Though advanced fossil systems have great potential for reduced impacts per unit of electricity, they will in the near future remain inferior compared to nuclear and renewables in terms of environmental damages.

Holistic evaluation of sustainability calls for explicit and possibly transparent consideration of economic and social factors (not addressed in this paper) besides ecology and health related issues. This can be addressed e.g. by using MCDA. The ongoing NEEDS project of the European Commission (2004-2008) continues the ExternE series, aiming at improving and integrating external cost assessment, LCA, and energy-economy modeling. Technology roadmap for electricity technologies up to year 2050 will be addressed using MCDA to reflect stakeholders' preferences [12].

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